"Photography of Sound-waves, and the Kinematographic Demonstration of the Evolutions of Reflected Wave-fronts." By R. W. WOOD, Assistant Professor of Physics in the University of Wisconsin. Communicated by C. V. BOYS, F.R.S. Received February 10,—Read February 15, 1900.

In a paper published in the 'Philosophical Magazine' (August, 1899) I gave an account of a series of photographs of sound-waves undergoing reflection, refraction, diffraction, &c., which were made chiefly for the purpose of illustrating certain optical phenomena to classes.

The waves were in every case single pulses in the air produced by electric sparks, illuminated and photographed by the light of a second spark, properly timed with reference to the first, the apparatus being essentially the same as that employed by Toepler for the study of striæ.

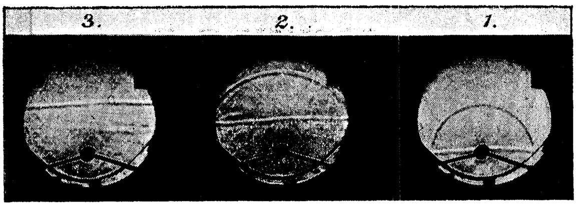
I have recently secured, by means of an improved apparatus, a very much better and more complete series of photographs; and at the risk of subjecting myself to criticism for bringing matter already published to the attention of the Society, I wish to devote a few minutes to a very rapid inspection of them.

The following cases, that were not represented in my first paper, I think I may safely comment upon.

The conjugate foci of the elliptical mirror, aplanatic for rays issuing from a point, is very beautifully shown, the spherical wave diverging from one focus being transformed by reflection into a converging sphere which shrinks to a point at the other focus.

The transformation of a spherical into a plane wave by a parabolic mirror is also well shown (fig. 1).

FIG. 1.

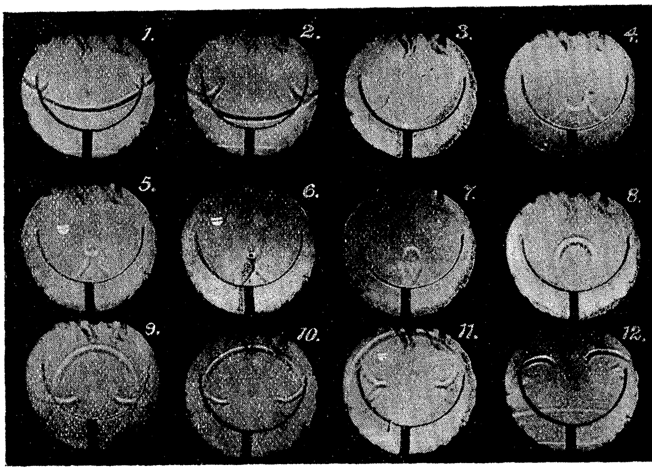


The effect of spherical aberration of circular mirrors is beautifully exhibited in several cases.

When a plane wave enters a hemispherical mirror the reflected wave front is cusped, and the cusp will be seen to lie always on the caustic surface. The form of the complete wave in this case is not unlike a

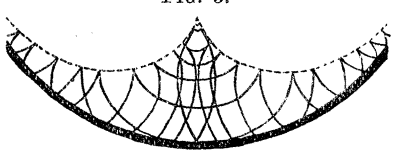
volcanic cone with a bowl-shaped crater, the bowl eventually collapsing to a point, at the focus of the mirror, the sides of the cone running in under it and crossing. From now on the wave diverges, and goes out of the mirror in a form somewhat resembling the bell of a medusa, the caustic form by twice-reflected rays being traced by a second cusp (fig. 2).

Fig. 2.



These forms can, of course, be constructed geometrically, and we have here a slide with a number of successive positions of the wave-front, showing how the cusps follow the caustic surface (fig. 3). The

Fig. 3.

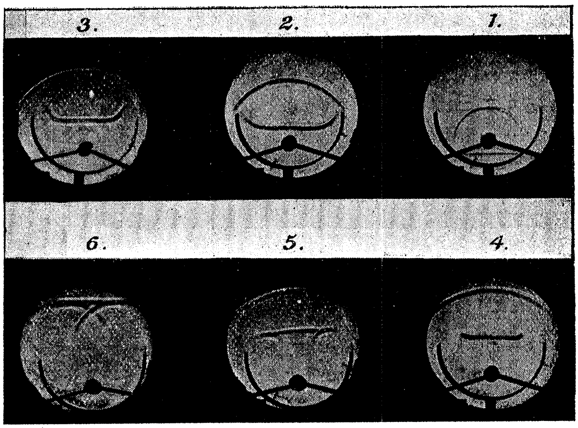


construction shows that there is a concentration of energy at the cusp; consequently we may define the cusp as a moving focus, and the caustic as the surface traced by it. Though I hesitate in claiming that this relation, at once so apparent, is at all novel, I may say that, so far as I have been able to find, it is not brought out in any of the text-books, caustic surfaces being invariably treated by *ray* rather than by *wave-front* methods.

If the wave starts at the principal focus of a hemispherical mirror, the reflected front is nearly plane in the vicinity of the axis, curling up at the edges, however. As this flat-bottomed saucer moves up, the

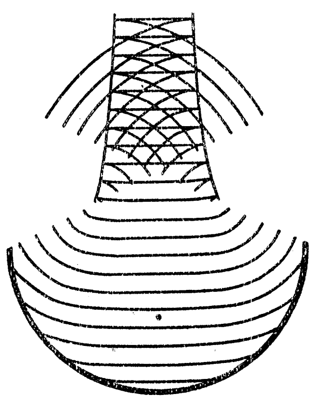
curved sides come to a focus along the circular edge of the flat bottom, so that in one position the front appears as a true plane (fig. 4); but

FIG. 4.



from this point on the curved sides, having passed through a focus, diverge again and follow the flat bottom. The cusp formed by the union of these two portions traces the caustic surface, which is in this case a very tapering funnel, as is shown well by the geometrical construction (fig. 5).

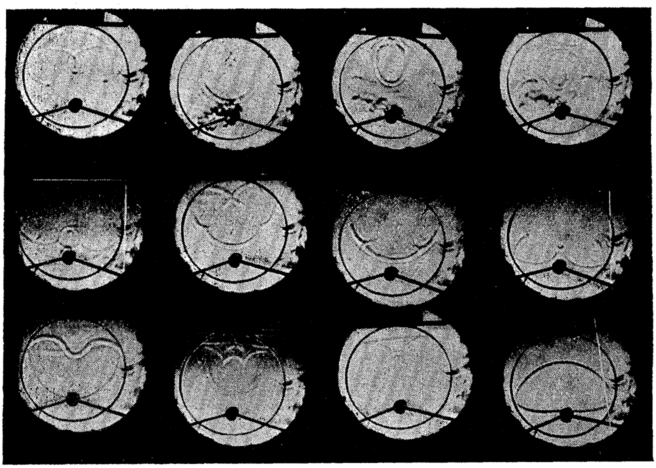
FIG. 5.



If now we substitute for the hemisphere a complete sphere, we obtain very complex forms which cannot be followed except by geometrical constructions, for the wave is shut up in the mirror and reflected back and forth, becoming more complicated at each reflection (fig. 6). That all of these very intricate forms can be constructed by

geometry I shall show presently; and by means of the animatograph, which Mr. Paul has most kindly placed at our disposal, we can actually see the wave going through its gymnastics.

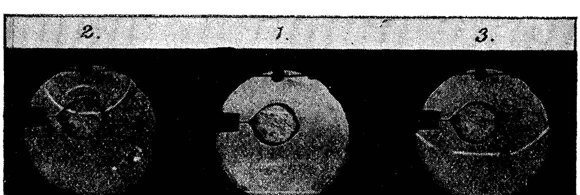
Fig. 6.



The principle of Huygens, that any small portion of a wave-front can be considered as the centre of a secondary disturbance, and that a small portion of this new disturbance can in turn be regarded as a new centre, can be shown by the sound-waves, as well as the obliteration of the shadow by diffraction, and the secondary wavelets reflected from corrugated surfaces, interesting in connection with the diffraction grating.

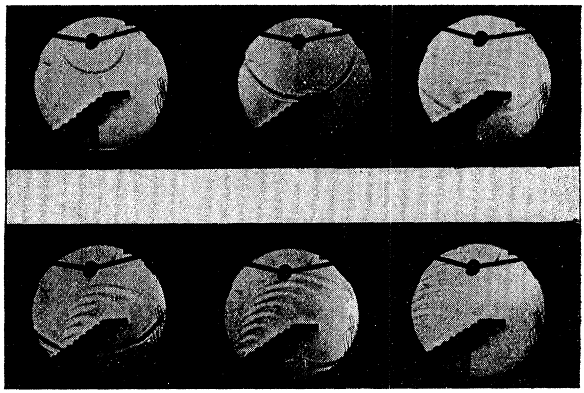
Various cases of refraction are also shown, the only novel one being the transformation of a spherical into a plane wave by a carbonic-acid lens. The construction of the cylindrical lens, of exceedingly thin collodion, a matter of considerable difficulty, was successfully accomplished, the circular flat ends of very thin mica, free from striæ, enabling the passage of the wave through the lens to be followed (fig. 7). The other cases of refraction have already been described, as

Fig. 7.



well as the very beautiful instance of the formation of a train of waves, or musical note, by the reflection of a single pulse from a steep flight of steps (fig. 8).

FIG. 8.



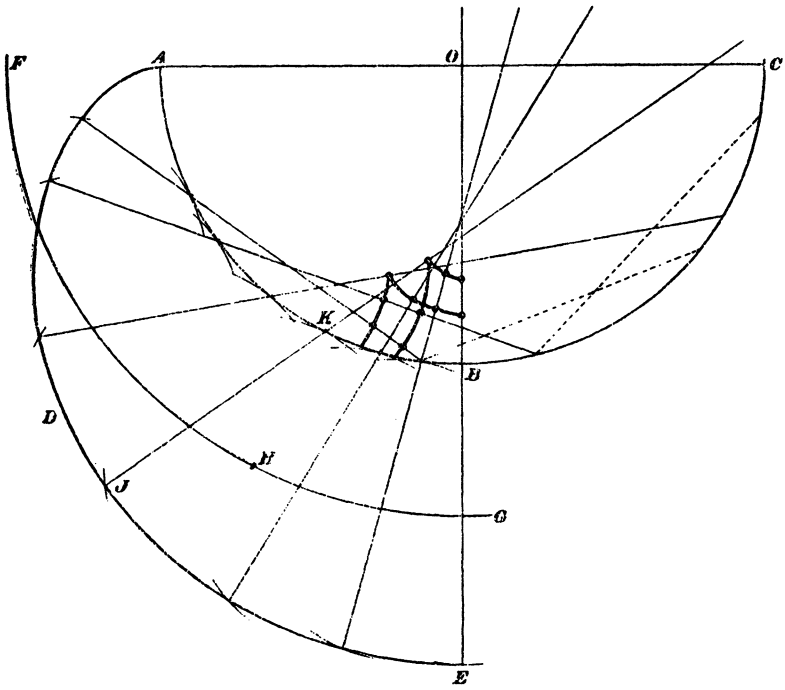
Returning now to the evolutions of plane and spherical waves after reflection from spherical surfaces, I wish to bring to the attention of the Society a method of demonstrating in a most graphic manner the progressive changes in the wave-front reflected under these conditions.

Having been unable to so control the time interval between the two sparks that a progressive series could be taken, I adopted the simpler method of making a large number of geometrical constructions, and then photographing them on a kinetoscope film.

As a very large number of drawings (100 or so) must be made if the result is to be at all satisfactory, a method is desirable that will reduce the labour to a minimum. I may be permitted to give, as an instance, the method that I devised for building the series illustrating the reflection of a plane wave in a spherical mirror. The construction is shown in the figure.

ABC is the mirror, AOC the plane wave. Around points on ABC as centres describe circles tangent to the wave. These circles will be enveloped by another surface, ADE, below the mirror (the orthogonal surface). If we erect normals on this surface, we have the reflected rays, and if we measure off equal distances on the normals, we have the reflected wave-front. By drawing the orthogonal surface we avoid the complication of having to measure off the distances around a corner. The orthogonal surface is an epicycloid formed by the rolling of a circle of a diameter equal to the radius of curvature of the mirror on the mirror's surface, and normals can be erected by drawing the

arc FG (the path of the centre of the generating circle), and describing circles of diameter BE around various points on it. A line joining the point of intersection of one of these circles with the epicycloid, and the point of tangency with the mirror, will, when produced, give



a reflected ray; for example, JK produced for circle described around H. This construction once prepared, the series of wave-front pictures can be very quickly made. Three or four sheets of paper are laid under the construction and holes are punched through the pile by means of a pin, at equal distances along each ray (measured from the orthogonal surface).

The centre of the mirror and the point where its axis meets the surface are also indicated in the same manner. The sheets are now separated, and corresponding pin-holes are united on each sheet by a broad black line, which represents the wave-front. After a time it becomes necessary to consider double reflections, and to do this we are compelled to construct twice-reflected rays (indicated by dotted lines), and measure around a corner each time.

About a hundred pictures are prepared for each series, and the pictures then photographed separately on the film, which, when run

Fig. 9.

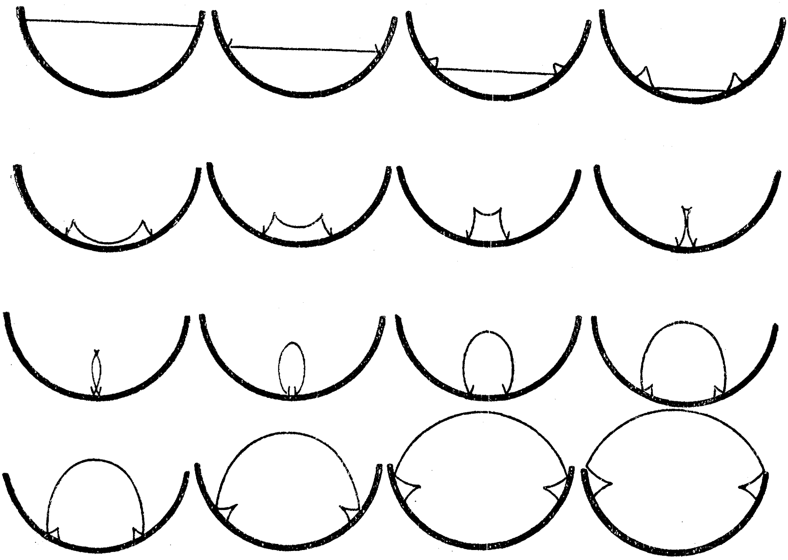
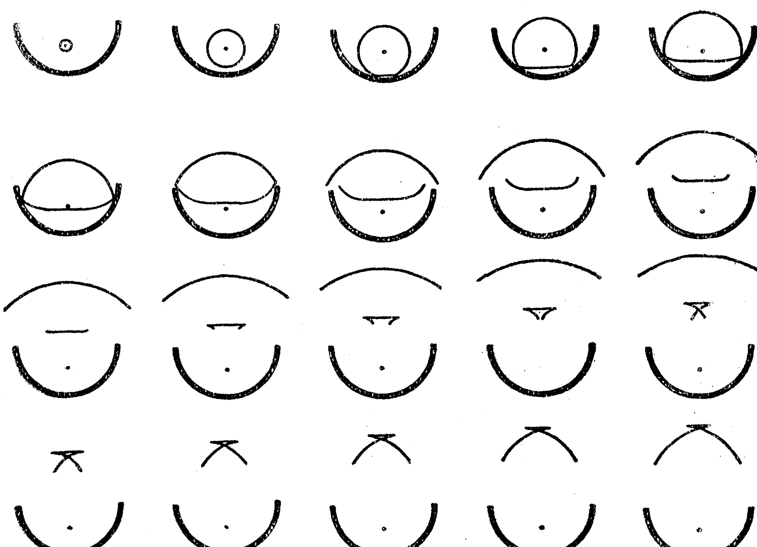


Fig. 10.

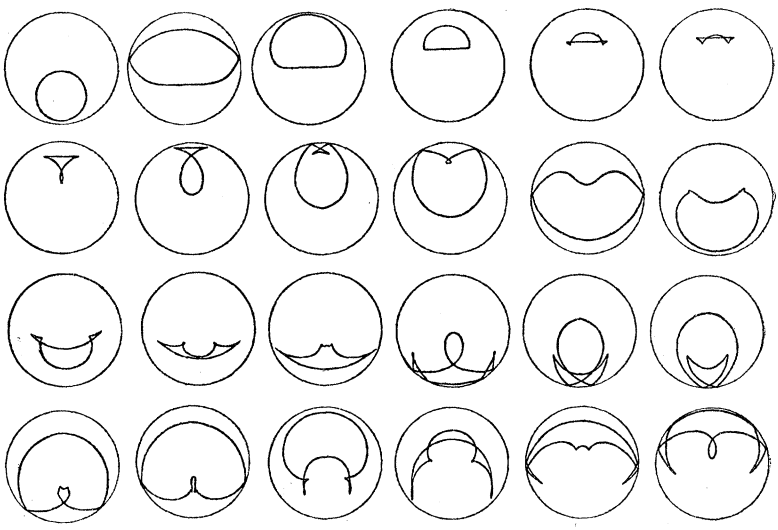


through Mr. Paul's animatograph, will give us a very vivid representation of the motion of the wave-front.

The series illustrating reflection inside of a complete sphere was the

most difficult to prepare, as several reflections have to be considered. It has been completed for three reflections, and Mr. Max Mason, of Madison, to whom I am greatly indebted for his patient work in assisting me, is going on with the series. As will be seen, the wave has already become quite complicated, and it will be interesting to see what further changes result after three or four more reflections. I am also under obligations to Professor A. B. Porter, of Chicago, who prepared the set of drawings illustrating the passage of a wave out from the principal focus of a hemispherical mirror.

Fig. 11.



A number of points taken at intervals along the film are here reproduced, and give a fair idea of the transformations. Fig. 9 shows the plane wave entering the hemispherical mirror, while in fig. 10 we have a spherical wave starting on the principal focus of a similar reflecting surface (compare fig. 9 with fig. 2, and fig. 10 with fig. 4). Fig. 11 shows the evolutions of the wave shut upon the complete spherical mirror, and shows the development of the complicated photographed forms shown in fig. 6.

FIG. 1.

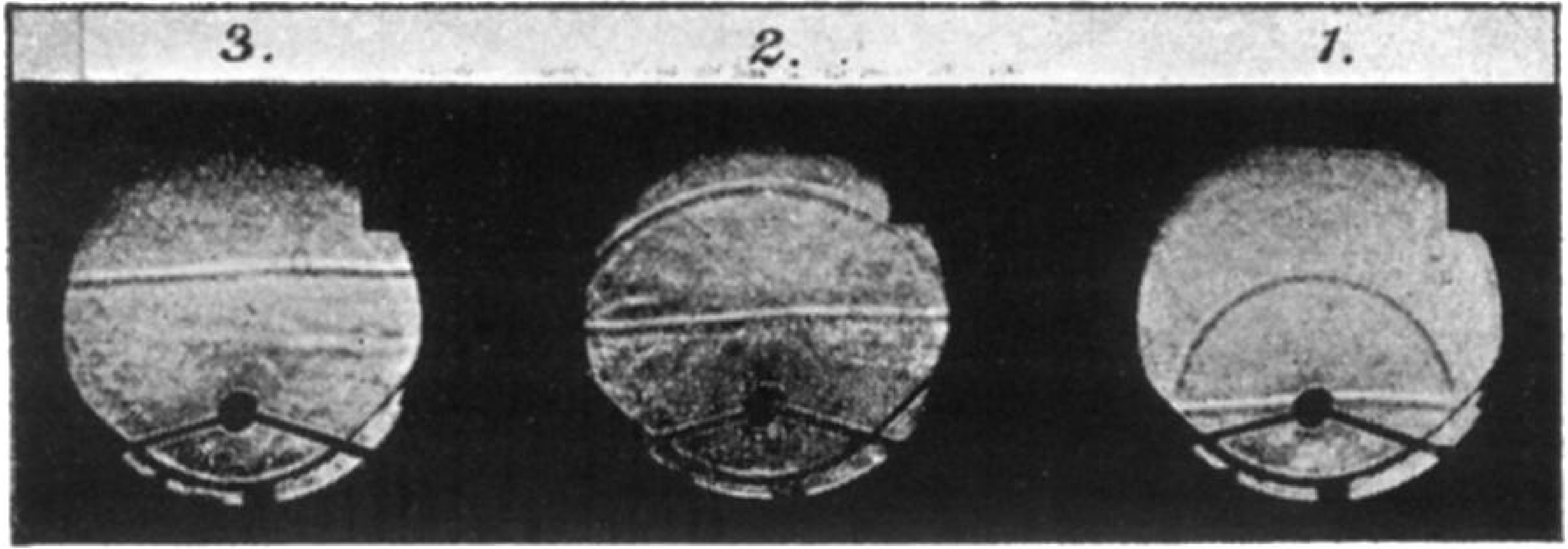


FIG. 2.

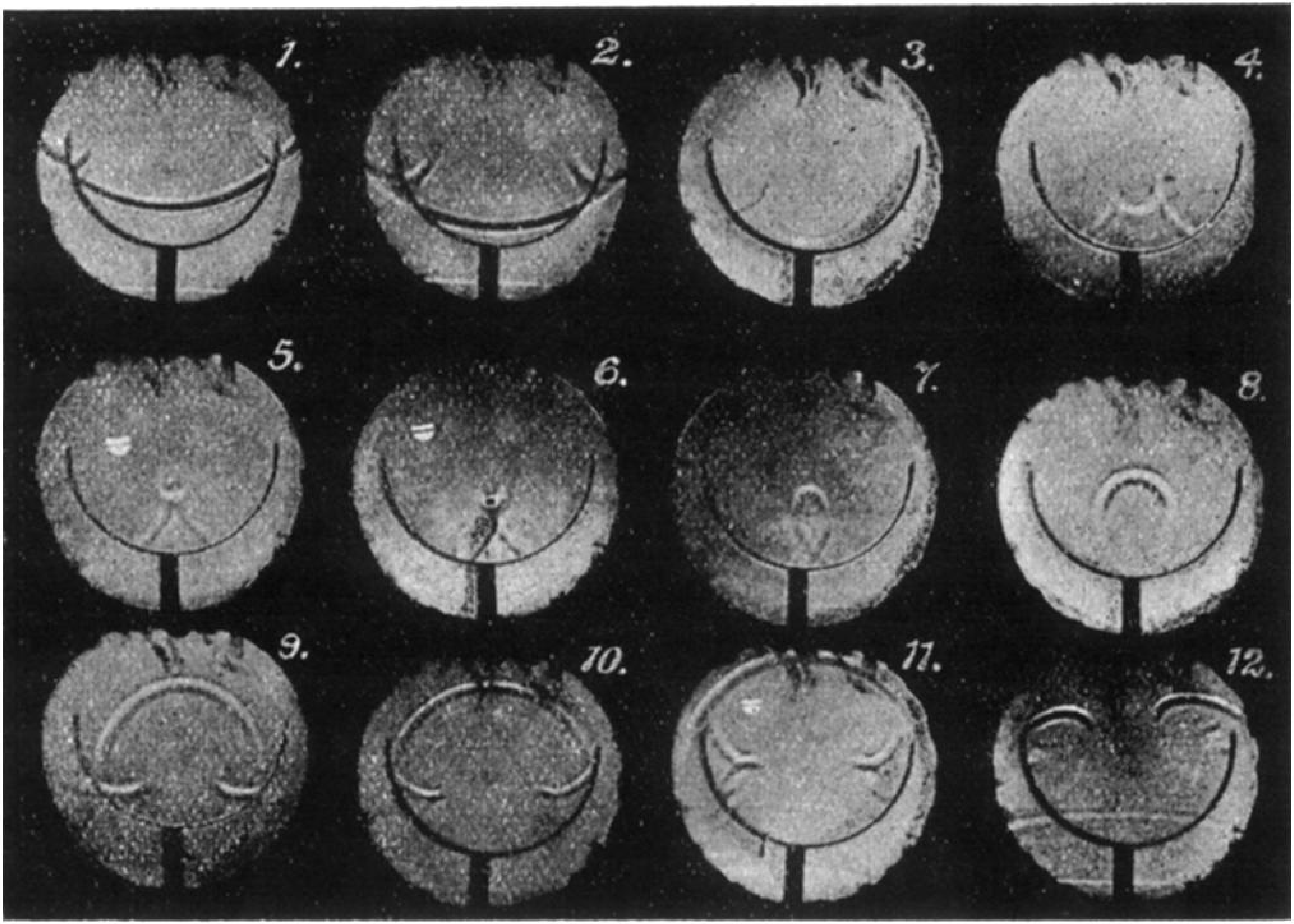


FIG. 4.

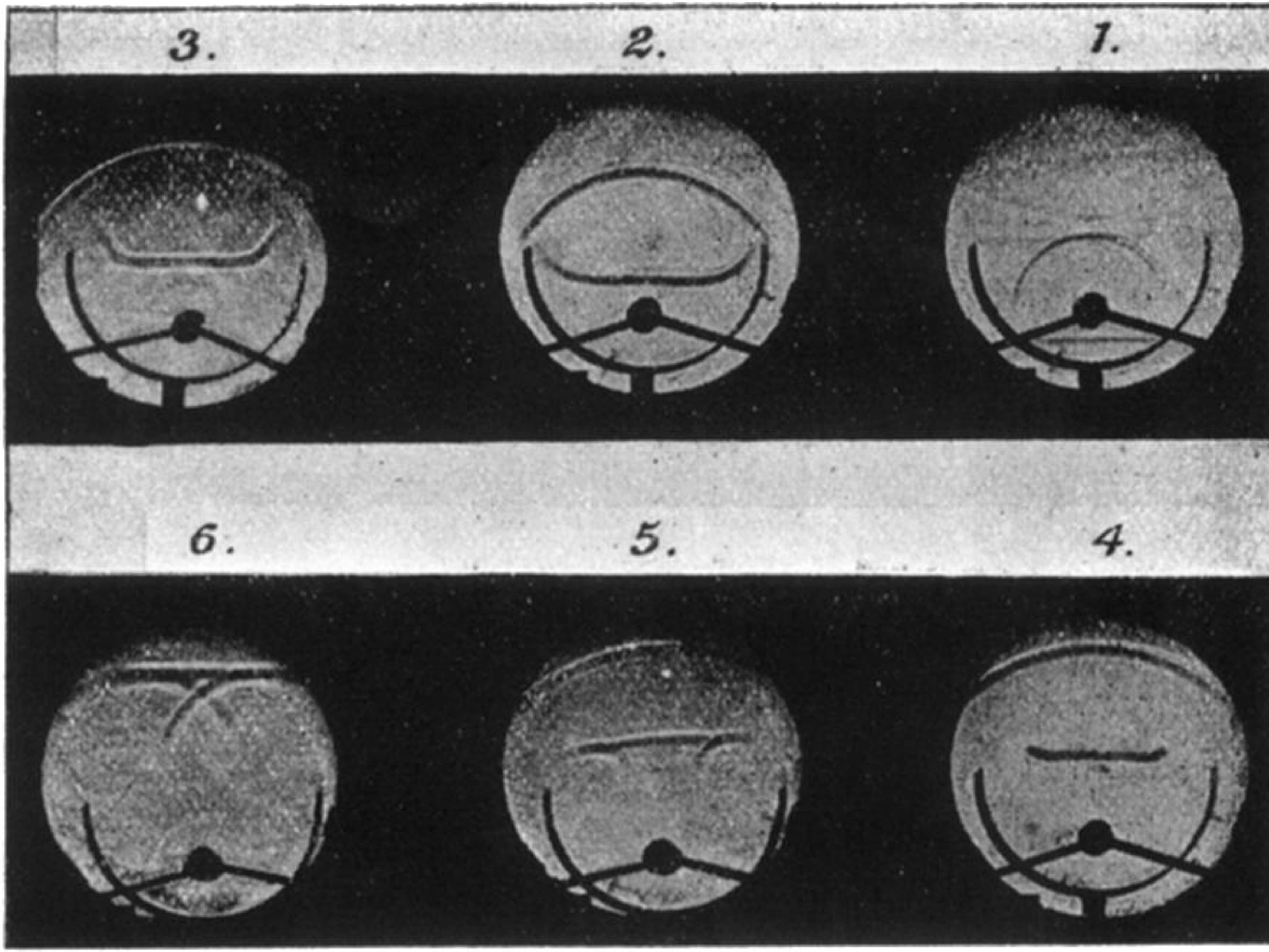


Fig. 6.

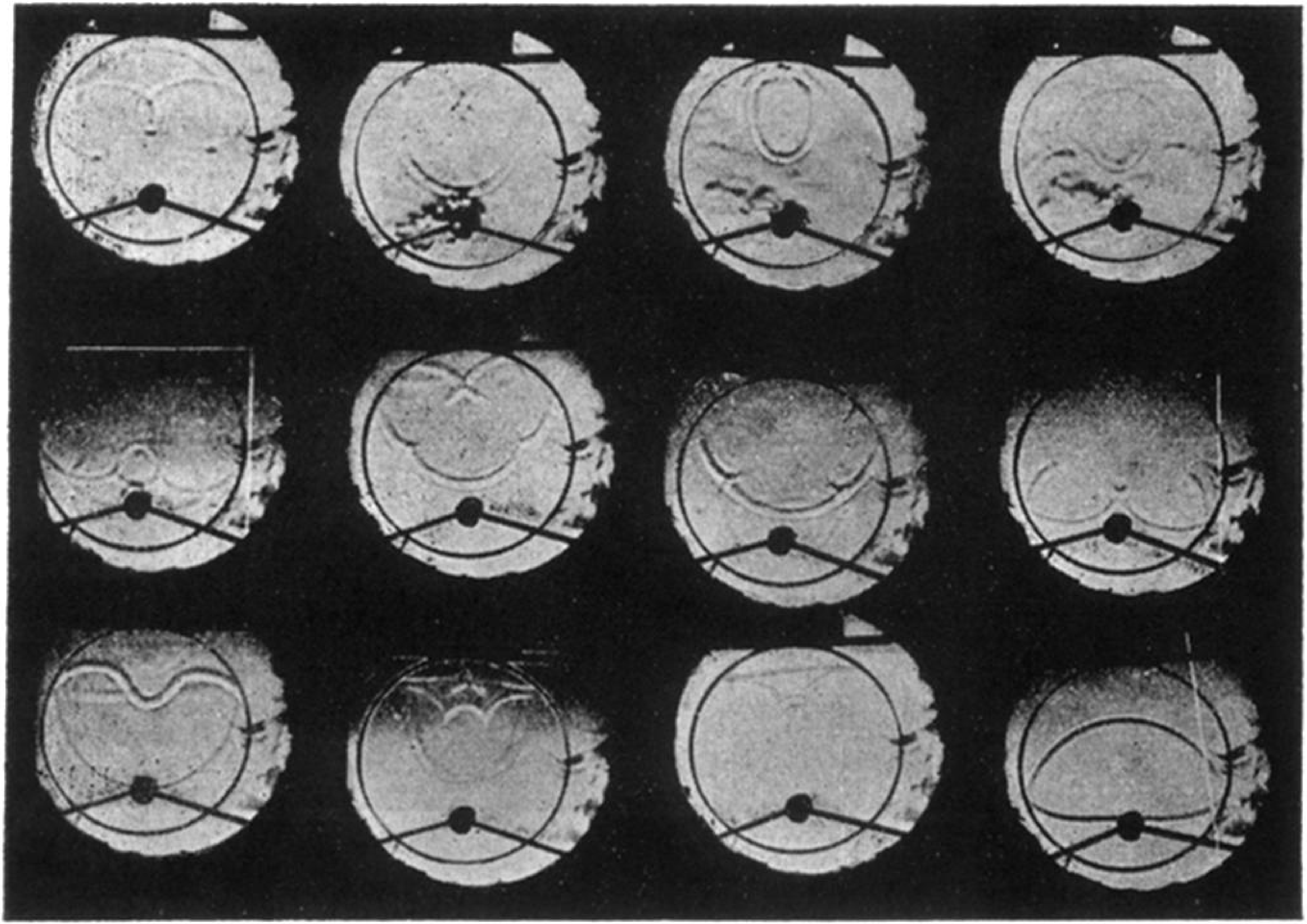


Fig. 7.

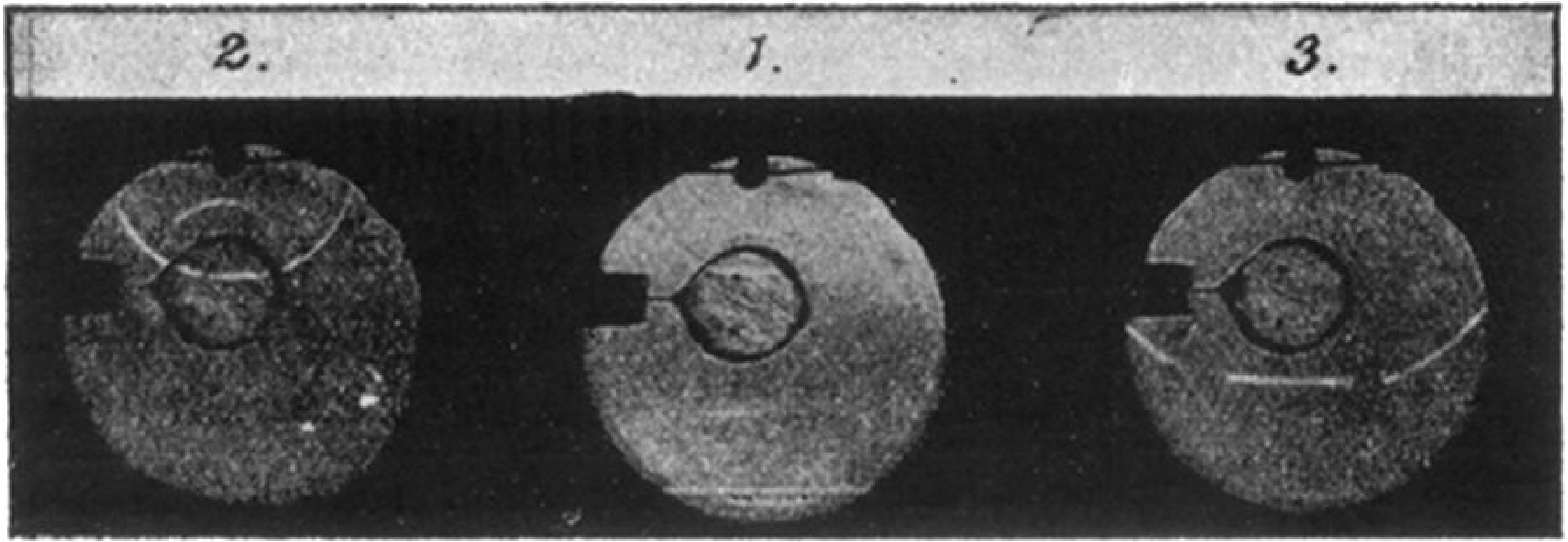


Fig. 8.